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Most large-scale network optimization problems exhibit structures that allow the possibility of attactk via algorithms what exhibit a high degree of parallelism. Such structure include quasi-indepent blocks of constraints for different commodities or time periods, and geographically disjoint components in approximating solutions. The emphases of our research have been the development of new parallel optimization techniques that utilize these and related features in order to take advantage of distributed computing environments. We have also udertaken a comparison of the relative efficiencies of approaches based on different computer architectures sucha s message-passing multicomputers and shared-memory multiprocessors. The parallel algorithms that we have implemented have made possible the solution of extremely large linear networks (with more than 1 million variables) and nonlinear network optimization problems with as many as 400,000 variables or relatively modest parallel computing systems, and have displayed excellent speedups relative to the corresponding single-processor programs.

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LARGE-SCALE OPTIMIZATION VIA DISTRIBUTED SYSTEMS

Robert R. Meyer
Center for the Mathematical Sciences and
Computer Sciences Department
University of Wisconsin-Madison
Madison, WI 53706

November 1, 1989

Final Technical Report for Period
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DEPARTMENT OF THE AIR FORCE
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Bolling Air Force Base, DC 20332-6448

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Robert R. Meyer

Center for the Mathematical Sciences and

Computer Sciences Department

University of Wisconsin-Madison

Summary

Most large-scale network optimization problems exhibit structures that allow the possibility of attack via algorithms that exhibit a high degree of parallelism. Such structures include quasi-independent blocks of constraints for different commodities or time periods, and geographically disjoint components in approximating solutions. The emphases of our research have been the development of new parallel optimization techniques that utilize these and related features in order to take advantage of distributed computing environments. We have also undertaken a comparison of the relative efficiencies of approaches based on different computer architectures such as message-passing multicomputers and shared-memory multiprocessors. The parallel algorithms that we have implemented have made possible the solution of extremely large linear networks (with more than 1 million variables) and nonlinear network optimization problems with as many as 400,000 variables on relatively modest parallel computing systems, and have displayed excellent speedups relative to the corresponding single-processor programs.

1. Research Objectives and Accomplishments

The research objectives were

1) the development of new parallel algorithms for the solution of large-scale nonlinear network optimization problems;

2) the development of a new class of barrier function methods applicable to multicommodity problems in order to utilize the nonlinear techniques of objective 1) in conjunction with a variant of interior point methods;

3) the development and testing of parallel algorithms for linear generalized network optimization with the goal of achieving high efficiency in a shared memory multiprocessor environment for problems with more than 1 million variables;

4) the implementation of a distributed version of the network simplex method for linear networks with hundreds of thousands of arcs;

5) the testing of these methods on representative sets of large-scale test problems.

These objectives were successfully accomplished. A summary of the results obtained in these areas is given below.

The research carried out under this grant on parallel algorithms for nonlinear networks led to the development and proof of convergence of a class of new methods based on decomposition. This approach involves the use of a variety of block separable approximations to decompose problems of the form:

$$\min f(x)$$

$$\text{s.t. } A_k x_k = b_k$$

$$l_k \leq x_k \leq u_k \quad (k = 1, \ldots, K)$$

(where A_k, b_k, l_k and u_k are the constraint data for commodity k) into single-commodity linear network subproblems. A key research issue resulting from this form of decomposition is the distribution of work between the "local views" in which single-commodity subproblems are solved in parallel and the "global view" or coordination phase in which data from the solution of many such subproblems are collected and modifications of these solutions are made as needed in order to achieve improvements in the original or barrier-augmented objective function (in which there is coupling between all commodities). In joint work with my Ph.D. student Gary Schultz [Schultz and Meyer 1989], we have generalized the earlier research of Chen and Meyer, which was supported by this grant, to allow multi-dimensional searches in the coordinating task and to incorporate more flexible acceptance criteria in the updating process. Tests of this approach on the Patient Distribution System problems of the Military Airlift Command using the Sequent Symmetry S-81 multiprocessor indicate at least an order of magnitude improvement in times over the much faster KORBX system.

In the area of generalized networks (also known as networks with gains and losses, since flows are allowed to change as they traverse links), we have developed [Clark and Meyer 1987] and [Clark and Meyer 1989] two new decomposition methods that provide superlinear speedups for certain subclasses and extend our earlier approach to large-grain problems (i.e., problems in which the collection of quasi-trees in the optimal solution consists of a small number of components each of which has a large number of nodes). These approaches have been implemented on the Sequent multiprocessor, and used to solve problems with more than 1 million variables.

The final research area that we have explored is the parallel implementation of the network simplex method for extremely large "pure" (as opposed to generalized) linear networks. The challenge in this area was to utilize appropriate data structures so that the pricing operation could be parallelized and overlapped with the pivoting operation. We have obtained superlinear speedups [Peters 1988] with this approach on the Sequent multiprocessor, testing the method on the new set of large-scale network test problems recently developed by Darwin Klingman and John Mote (of the University of Texas at Austin) as well as expanded versions of these problems with up to 500,000 arcs.

2. Publications

R. J. Chen and R. R. Meyer: "A Scaled Trust Region Method for a Class of Convex Optimization Problems", Technical Report #675, Computer Sciences Department, University of Wisconsin-Madison, 1987.

R. J. Chen: "Parallel Algorithms for Convex Optimization Problems", Ph.D. thesis, Computer Sciences Department, University of Wisconsin-Madison, 1987.

R. Clark and R. R. Meyer: "Multiprocessor Algorithms for Generalized Network Flows", Technical Report #739, Computer Sciences Department, University of Wisconsin-Madison, 1987.

J. Peters: "A Parallel Algorithm for Minimal Cost Network Flow Problems", Technical Report #762, Computer Sciences Department, University of Wisconsin-Madison, 1988, to appear in *Networks*.

M. D. Chang, M. Engquist, R. Finkel and R. R. Meyer: "A Parallel Algorithm for Generalized Networks", *Annals of Operations Research* **14**, 125–145, 1988.

R. J. Chen and R. R. Meyer: "Parallel Optimization for Traffic Assignment", *Mathematical Programming, Series B* **42**, 327–345, 1988.

R. R. Meyer and S. Zenios: "Parallel Optimization on Novel Computer Architectures", *Annals of Operations Research* **14**, 1988.

O. L. Mangasarian and R. R. Meyer: "Parallel Methods in Mathematical Programming", *Mathematical Programming* **42**, 1988.

G. Schultz and R. R. Meyer: "A Flexible Parallel Algorithm for Block-Constrained Optimization Problems", in *Impact of Recent Computer Advances on Operations Research*, R. Sharda, et al., eds., Elsevier Publishing, 1989.

R. Clark and R. R. Meyer: "Parallel Arc-Allocation Algorithms for Optimizing Generalized Networks", Technical Report #862, Computer Sciences Department, University of Wisconsin-Madison, 1989, (to appear in Proceedings of Workshop on Supercomputers and Large-Scale Optimization).

3. Participating Professionals

Research Assistants (graduate students supported under this grant):

R. J. Chen - Ph.D. in Computer Sciences completed, 6/87

R. Clark - Ph.D. in Computer Sciences completed, 8/89

G. Schultz - passed Ph.D. Screening Examinations, 10/88.

4. Interactions

Invited papers presented by R. R. Meyer:

10/86 - ORSA/TIMS National Meeting: "Trust Region Methods for Nonlinear Networks"

4/87 - University of Maryland Workshop on Scientific Computing Using Parallel Architectures: "Parallel Algorithms for Network Optimization"

5/87 - ORSA/TIMS National Meeting: "A Parallel Trust Region Algorithm"

5/87 - SIAM Conference on Optimization: "Parallel Algorithms for Large-Scale Nonlinear Networks"

6/87 - NATO Advanced Research Workshop on Algorithms and Problem Formulations in Mathematical Programming: "Modelling for Parallel Optimization"

8/87 - Symposium on Parallel Optimization: "Parallel Algorithms for Large-Scale Network Optimization"

12/87 - Third SIAM Conference on Parallel Processing: "Parallel Optimization of Large-Scale Linear Networks"

4/88 - ORSA/TIMS National Meeting: "Parallelizing the Network Simplex Method"

5/88 - University of Minnesota Workshop on Supercomputers and Large-Scale Optimization: "Parallel Computing for Large-Scale Network Optimization"

8/88 - 13th International Symposium on Mathematical Programming - Tokyo: "Parallel Algorithms for Large-Scale Network Optimization Problems", "Parallel Optimization of Nonlinear Networks"

10/88 - ORSA/TIMS National Meeting - Denver: "Parallel Algorithms for Traffic Assignment"

1/89 - ORSA (Comp. Sci. Tech. Section) Conference on Impact of Recent Computer Advances on Operations Research - Williamsburg: "Parallel Computation in Large-Scale Network Optimization"

1/89 - Programacion Matematica '89 - Madrid: "Parallel Algorithms for Linear Network Flows", "Parallel Algorithms for Nonlinear Network Flow Optimization"

Interactions with AFOSR:

3/87 - Visited by Dr. Samuel Rankin, AFOSR, to discuss research directions relevant to an AFOSR initiative in parallel optimization

4/87 - Visit to Mathematical and Information Sciences Directorate, AFOSR, to discuss research directions relevant to parallel optimization

Other Consulting and Advising:

12/86 - Member of NSF site visit team evaluating a University of Michigan proposal to the Coordinated Experimental Research Program

9/87 - Member of NSF site visit team evaluating University of Minnesota and University of Colorado Coordinated Experimental Research Programs

Reviewer for numerous AFOSR and NSF grant proposals.

5. Other Professional Activities Related to Research

Co-editor of proceedings of AFOSR-sponsored Symposium on Parallel Optimization, *Mathematical Programming*, Series B, vol. 42, no. 2, 1988, (see Appendix).

Co-editor of Committee on Algorithms Newsletter (Math. Programming Society).

Area Editor, Parallel Computation, Journal on Computing (a new journal of the Operations Research Society).

APPENDIX

SYMPOSIUM ON PARALLEL OPTIMIZATION

Olvi L. Mangasarian Robert R. Meyer	Computer Sciences Department University of Wisconsin 1210 West Dayton Street Madison, WI 53706

With AFOSR and ONR support the following eighteen papers were presented at the Symposium on Parallel Optimization held in Madison, August 10-12, 1987:

George B. Dantzig: "Planning under uncertainty using parallel computing"

Stavros A. Zenios & John M. Mulvey: "Nonlinear network programming on vector supercomputers"

Dimitri P. Bertsekas: "Parallel relaxation methods for linear network flow problems"

Ron S. Dembo & Partrick Hénaff: "Vectorized conjugate gradient projection methods:

Shih-Ping Han: "Parallel quasi-Newton algorithms for nonlinear programming"

Michael D. Chang, Michael Engquist, Raphael A. Finkel & Robert R. Meyer: "Solving multiperiod generalized network problems on a parallel computer"

Robert R. Meyer: "Parallel algorithms for large-scale network optimization"

Alexander H.G. Rinnooy Kan: "Parallel partitioning methods"

J. Ben Rosen & Andrew Phillips: "Multitasking and parallel algorithms for linearly constrained global optimization"

Klaus Ritter: "On the use of parallel computing and automatic differentiation in mathematical programming"

Robert Schnabel, Richard H. Byrd & G. Shultz: "Speculative function evaluation in parallel optimization"

Yair Censor: "Parallel and block-iterative methods with applications in medical imaging and radiation therapy"

Jong-Shi Pang: "Parallel Newton methods for complementarity problems"

Lucio Grandinetti: "Applications of vector computers to optimization of large scale systems"

A. Ech-cherif, Joseph G. Ecker & M. Kupferschmid: "A parallel algorithm for nonlinear programming on the hypercube"

James K. Ho: "Linear programming decomposition"

Danny Sorensen: "Programming methodology and performance issues for advanced computer architecture"

Olvi L. Mangasarian & Renato De Leone: "Serial and parallel successive overrelaxation in linear and quadratic programming"

This symposium, the first of its kind in the field of optimization, addresses the very important and promising area of parallel computation. Sixty-three persons attended the symposium. Proceedings of the symposium will be published as a special issue of the journal Mathematical Programming Studies.